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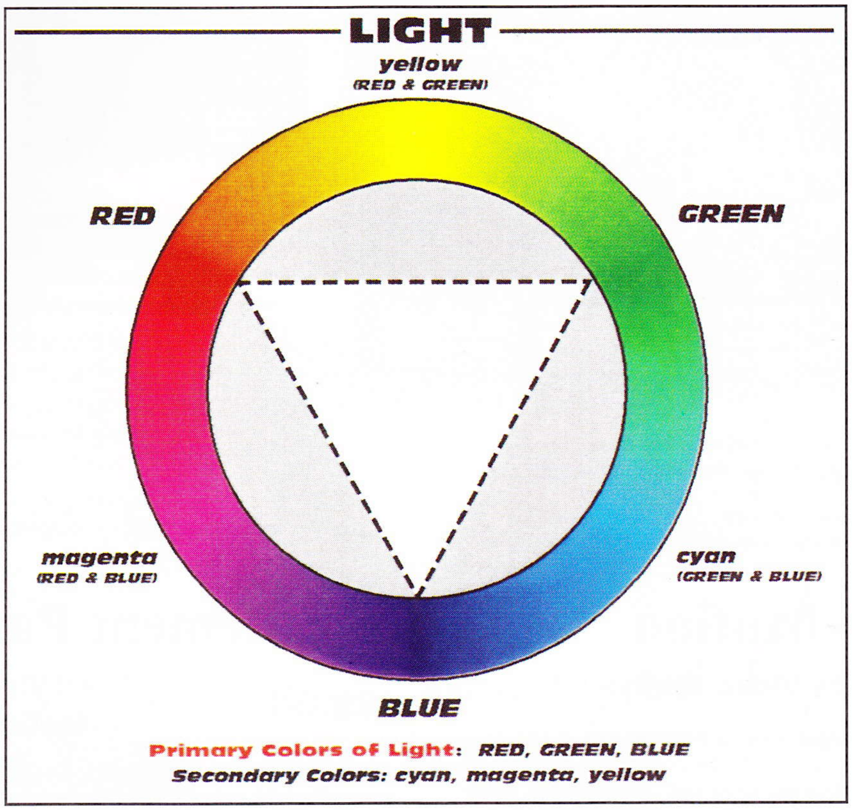

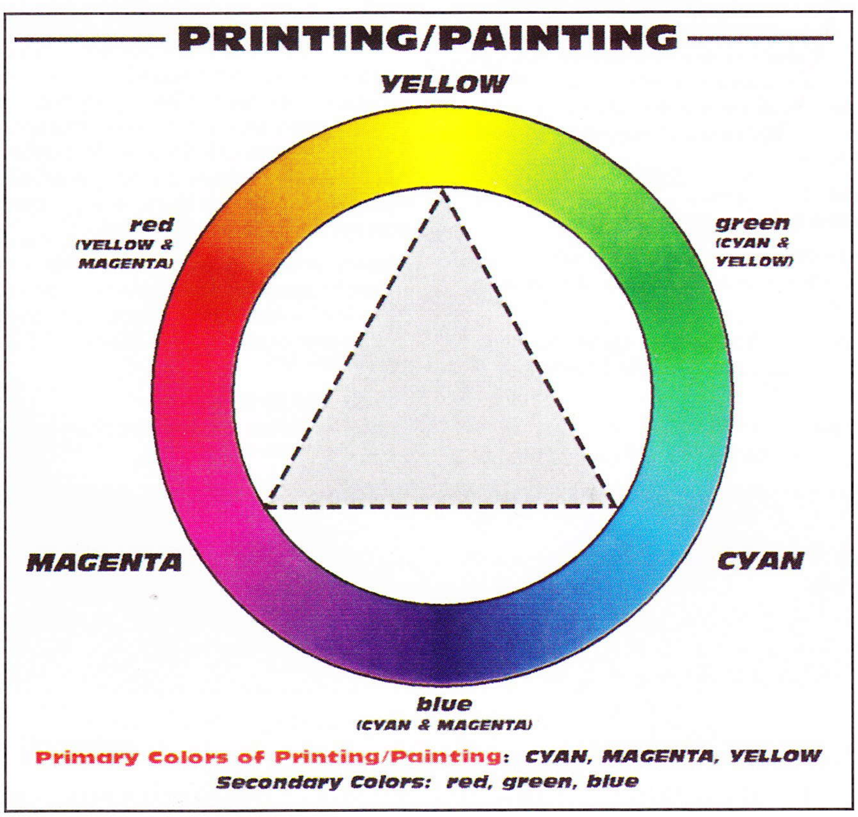

NOTE

Confusing Color Concepts Clarified

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Students study color concepts starting in elementary-school art classes and continuing in advanced art, printing, computer science, and/or physics classes. Yet, the primary colors, complementary colors, and the color wheel that are taught are often different. The identification and clarification of these differences and some hands-on experiments that elucidate these color concepts are described here. The approach expands on that of a previous *TPT* article.[1]

Additive Colors

Primary colors are defined by two characteristics[2]: (1) No combination of two primary colors can produce a third primary color; and (2) Combining the three primary colors can produce a wider range of colors than using any other three colors. The primary additive colors of light are generally, and correctly, discussed in physics texts to be red, green, and blue. Additive color mixing can be described using "color math" as follows:

Green + Blue = Cyan (1)

Blue + Red = Magenta (2)

Red + Green = Yellow (3)

These relationships can be verified by students by examining how colors are made on a computer screen using an 8x magnifier.

At this stage, the relationship of color mixing to the color wheel can be made. If it is not, then the color wheel may be viewed as a model that describes color for artists, but does not have any relationship to physics. In fact, a simple color wheel that models Eqs. (1) through (3) is easily generated. In the color wheel shown in Fig. 1, yellow light is between red light and green light, because it results from the mixing of these colors of light. Similarly, cyan is between green and blue, and magenta is between blue and red.

Students can also investigate with a magnifier how white is produced on a computer monitor: the white background actually consists of small red, green, and blue lights. Using color math, we can write these results as:

Red + Green + Blue
= White (4)

The concept of complementary colors also can be demonstrated using the color wheel as well as color math. Complementary colors of light are those two colors that when added together produce white. Now it is quite easy to see that, for example, yellow and blue are complementary colors of light:

Yellow + Blue
= (Red + Green) + Blue
= White (5)

Red and cyan are also complementary colors, as are green

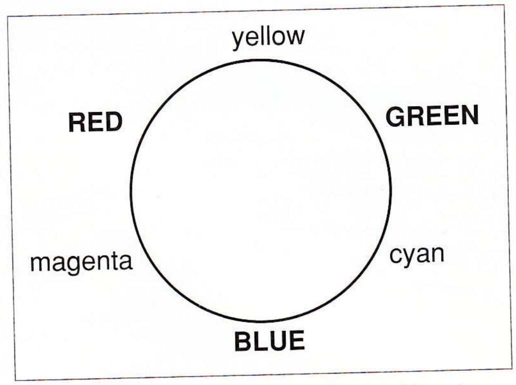

Fig. 1. Color wheel for additive color mixing. The primary colors are red, green, and blue.

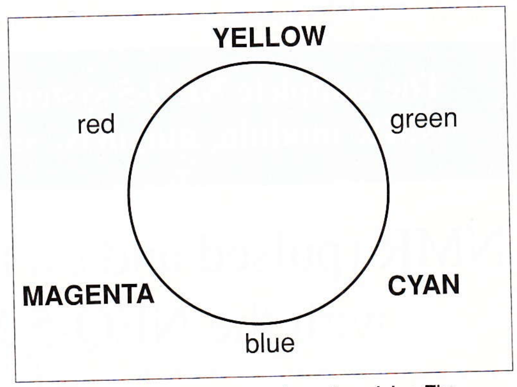

Fig. 2. Color wheel for subtractive color mixing. The primary colors are cyan, magenta, and yellow.

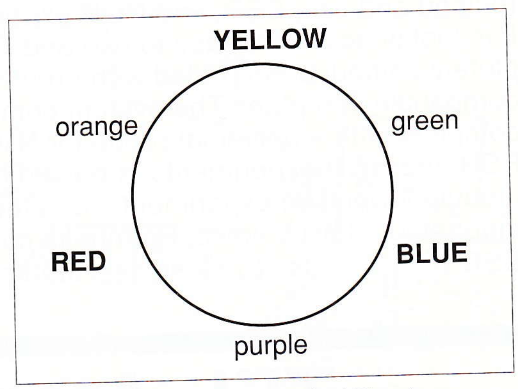

Fig. 3. Traditional painter's color wheel. The primary colors are red, yellow, and blue.

and magenta. The color wheel provides a nice way to view complementary colors: they lie on opposite sides of the color wheel.

Subtractive Colors

The primary subtractive colors are cyan, magenta, and yellow. This is generally correctly described in physics texts and is also well known to printers. But if you ask an artist or look in art books, the primary colors of painting are red, yellow, and blue. This inconsistency is rarely addressed by either physics texts or art books, leaving the misconception that somehow primary subtractive colors in physics or printing are different from those of painting.

Subtractive color mixing can also be described using "color math" using the following two steps. First,

White – Red = Cyan
(Cyan pigment) (6)

White – Green = Magenta
(Magenta pigment) (7)

White – Blue = Yellow
(Yellow pigment) (8)

These equations demonstrate that, for example, we see the color of an object as cyan because it subtracts a single primary color of light, namely red, from the incident white light. The primary subtractive colors are so-called because they subtract one of the primary colors of light from the incident white light.

Subtractive color mixing occurs when two primary subtractive colored objects overlap (denoted below by the symbol "/") so that both objects subtract colors from the incident white light. Therefore, this can be written:

White – Red – Green = Blue
(Cyan/magenta pigments) (9)

White – Green – Blue = Red
(Magenta/yellow pigments) (10)

White – Blue – Red = Green
(Yellow/cyan pigments) (11)

For example, Eq. (9) represents a cyan object overlapping a magenta object (cyan/magenta). In this case, the cyan object absorbs the red light from the incident white light, while the magenta object absorbs the green light, so that the object appears blue.

A color wheel that models Eqs. (9) through (11) is again easily generated and is shown in Fig. 2. For example, Eq. 9 indicates that mixing cyan and magenta pigments produces blue. So in the color wheel, blue is between cyan and magenta. Similarly, red is between magenta and yellow, and green is between yellow and cyan.

The concept of complementary colors can again be demonstrated using the color wheel and color math.

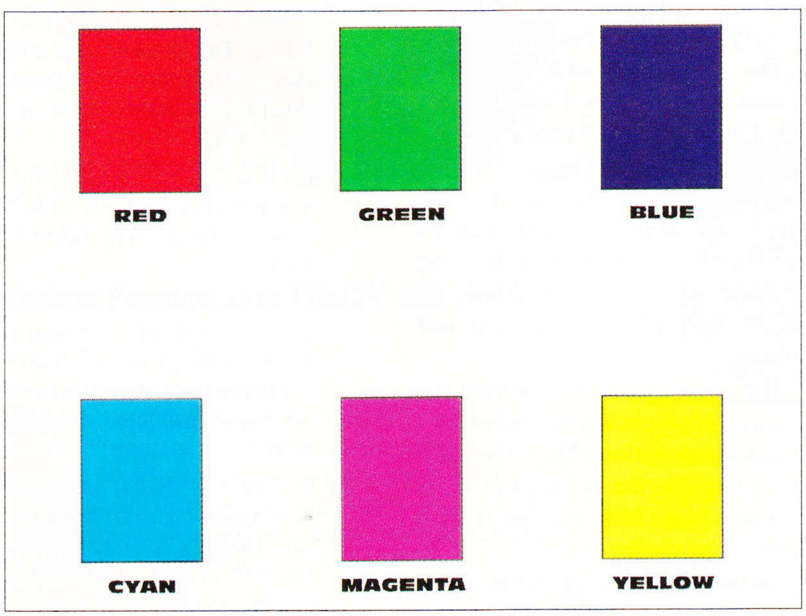

Fig. 4.

Complementary colors of pigments are those two colors that, when overlapped, produce black. It is apparent that yellow and blue are complementary subtractive colors, since yellow pigment absorbs blue light and blue pigment absorbs red and green light:

$$\begin{aligned} &\text{White} - \text{blue} - (\text{red} + \text{green}) \\ &\quad = \text{White} - (\text{red} + \text{green} + \text{blue}) \\ &\quad = \text{White} - \text{white} = \text{black} \\ &\quad (\text{Yellow/blue pigments}) \end{aligned} \qquad (12)$$

Red and cyan are also complementary colors of pigment, as are green and magenta. Again, complementary colors of pigments lie on opposite sides of the color wheel.

Except for the switching of the primary colors from red, green, blue to cyan, magenta, yellow, the color wheel for light (additive colors) shown in Fig. 1 is the same as the color wheel for pigments (subtractive colors) shown in Fig. 2! (Also see cover of this issue.)

Color Misconceptions

Many factors contribute to continued misconceptions about color.[3-6] Art books may confuse additive primaries with subtractive primaries, or confuse mixing light with mixing pigments.[7] But perhaps the most significant one is the incorrect color wheel that most artists use and to which most students are introduced in elementary school. This traditional color wheel was used by Goethe as early as 1793.[3] It is still used, apparently because it is sufficiently successful in describing color mixing, and because of its widespread acceptance and persistence in current teaching materials. The long history and variety of color wheels and models are described in a number of publications.[3-6]

In the traditional color wheel (Fig. 3), which is used for painting, the primary colors are red, yellow, and blue; these colors were chosen apparently because of their vivid distinctness.[8] It shows that mixing red and yellow produces orange, mixing blue and yellow produces green, and mixing red and blue produces purple, as shown by this color wheel. There are many ways to demonstrate that this color wheel is incorrect. Complementary colors should lie across from each other on the color wheel—in the traditional color wheel, they don't. Red, yellow, and blue are stated to be the primary colors (of paint or pigment). Recall that a primary color cannot be made from mixing two other primary colors. Yet, a red pigment can be made by mixing yellow and magenta pigments and blue can be produced by mixing cyan and magenta pigments. So red and blue cannot be primary colors of paint!

Another difficulty in demonstrating color mixing is the lack of commercially available materials with correct optical properties. While color paddles or films are available from a number of vendors, none of them are of the correct color to easily demonstrate the desired color mixing. For this reason, the author developed films and other color mixing materials with the correct optical properties.[9] Comparable colored films can also be made by printing large red, green, blue, cyan, magenta, and yellow rectangular colored areas (see Fig. 4) on ink-jet transparency paper using an ink-jet printer.[10] The use of these films clearly demonstrates the color mixing properties and complementary colors previously discussed.

The naming of colors also contributes to confusion. Cyan is often called blue, because it appears to be a light or sky blue. Cyan is often not used because the word is not in common usage. Magenta is often called red. Therefore, a printer may be using the colors of cyan, magenta, and yellow, but will call them blue, red, and yellow!

The sensitivity of the human eye to different colors also is a source of color misconceptions. We do not easily distinguish the color cyan from the color blue. Magenta and red are also seen as similar colors.

Further information about these and related experiments[10] and associated materials[9] are available from the Sciences Education Foundation–General Atomics.[11]

Acknowledgment

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